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ABSTRACT

During the last 10 years, cognitive science researchers have produced research findings that have great potential for increasing students' understanding of science. However, commercial publishers continue to produce textbooks and teacher's guides in traditional ways. This project developed a prototype unit which used an alternative approach to curriculum development. The unit was a rewritten version of the existing "Models of Matter" unit. The curricular decisions were based on an extensive program of research in student conceptions and classroom teaching using preclinical interviews, pretests, classroom observations, journals by collaborating teachers, post-clinical interviews, and posttests. Five curricular issues discussed are: (1) macroscopic and molecular conceptions; (2) epistemological status of molecules; (3) physical characteristics of molecules; (4) nature of scientific explanations; and (5) need to balance scientific elegance and student comprehension. This paper argues that fundamental rethinking of science education curriculum is in order and research findings can be used to improve student achievement in science in basic areas such as kinetic molecular theory. (Author/YP)

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TO REASON ABOUT CURRICULUM

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The Institute for Research on Teaching was founded in 1976 at Michigan State University and has been the recipient of major federal grants. Funding for IRT projects is currently received from the U.S. Department of Education, Michigan State University, and other agencies and foundations. IRT scholars have conducted major research projects aimed at improving classroom teaching, including studies of classroom management strategies, student socialization, the diagnosis and remediation of reading difficulties, and school policies. IRT researchers have also been examining the teaching of specific school subjects such as reading, writing, general mathematics, and science and are seeking to understand how factors inside as well as outside the classroom affect teachers. In addition to curriculum and instructional specialists in school subjects, researchers from such diverse disciplines as educational psychology, anthropology, sociology, history, economics, and philosophy cooperate in conducting IRT research. By focusing on how teachers respond to enduring problems of practice and by collaborating with practitioners, IRT researchers strive to produce new understandings to improve teaching and teacher education.

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Abstract

This paper focuses on the curricular problems involved in designing a sixth-grade "Matter and Molecules" unit, using a curriculum development model based on conceptual change research. The paper contrasts curricular decisions with the unit's commercial predecessor, the "Models of Matter" unit in the Houghton Mifflin Science sixth-grade text (Berger, Berkheimer, Neuberger, & Lewis, 1979). The major goal of the unit was the same in its original and revised version: to teach students to use the kinetic molecular theory (the idea that all substances are made of molecules that are constantly in motion) to explain the nature and structure of matter and physical changes of matter, including dissolving, expansion and compression of gases, thermal expansion, and changes in state.

The curricular decisions were based on an extensive program of research on student conceptions and classroom teaching using preclinical interviews, pretests, classroom observations, journals by collaborating teachers, post-clinical interviews, and posttests. Data and information from these sources were used as the basis for describing and justifying the changes that were made to improve the unit. We argue that fundamental rethinking of science education curriculum clearly is in order and it seems that research in cognitive structure and conceptual change could play an important role in such a process. This paper is an attempt to make explicit the relationship between conceptual change research and the curricular decision-making process. We argue that although curriculum decision making is a difficult, time-consuming process, research findings can be used to improve student achievement in science in basic areas such as the kinetic molecular theory.

USING CONCEPTUAL CHANGE RESEARCH
TO REASON ABOUT CURRICULUM

Glenn D. Berkheimer, Charles W. Anderson, and Steven T. Spees¹

The kinetic molecular theory is fundamental to the understanding of most of modern science. Feynman and colleagues recognized this when they said,

If, in some cataclysm, all scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or the atomic fact, or whatever you wish to call it) that all things are made of atoms--little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied. (Feynman, Leighton, & Sands, 1963, p. 1.2)

The kinetic molecular theory is of fundamental importance in science due to its usefulness in explaining phenomena and changes in substances. For example, in biology it is used to explain basic processes such as diffusion, osmosis, photosynthesis, and respiration. In earth science we use it to explain thermal expansion of solids, liquids, and gases; changes in density; and convection currents. In chemistry and physics we use the kinetic molecular theory to explain the nature of matter, changes of state of matter, pressure, the gas laws, and essential interactions among molecules that give rise to chemical reactions. It is, therefore, essential that students understand the kinetic molecular theory in sufficient depth so they can use it to understand and explain key processes and concepts in science.

Since the kinetic molecular theory is fundamental to the understanding of

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most of modern science, one might assume that it would be a cornerstone of the K-12 science curriculum. This is not the case, however. In an informal survey of K-12 science textbooks, we found few systematic attempts to help students understand the kinetic molecular theory. Most of the elementary science textbook series mention atoms and molecules but do not teach other aspects of the kinetic molecular theory, such as the idea that molecules are in constant motion or that when a substance is heated the molecules move faster. A few elementary science series at present use these basic ideas about the kinetic molecular theory (Cohen, DelGiorno, Harlan, McCormack, & Staver, 1984; Mallinson, Mallinson, Smallwood, & Valentino, 1985). The discussions are brief, however; the basic assumption seems to be that the kinetic molecular theory is relatively easy for elementary school students to learn and that they have no prior knowledge that interferes with this learning.

At the middle school level most of the science books illustrate the arrangement of molecules within different states of matter with a series of dots and indicate that the molecules are moving. However these same textbooks generally present the kinetic molecular theory simply as a fact to be learned, rather than showing how it can be used to explain common phenomena. We found only one book that attempted to teach the aspects of the kinetic molecular theory (Leyden, Johnson, & Barr, 1988) but even this book did not use the kinetic molecular theory to explain common phenomena.

High school texts, on the other hand, generally do not teach the kinetic molecular theory, but they do explain phenomena in ways that cannot be understood without a good understanding of the kinetic molecular theory. This pattern is typical of biology texts' (Koromond & Essenfield, 1988; Otto & Towle, 1985) treatment of processes such as diffusion, photosynthesis, respiration, and digestion. For example, Koromond and Essenfield state the

following:

Many multiple cellular animals are small and live in water. The cells of these organisms are in constant contact with the water and oxygen, and carbon dioxide can easily cross cell membranes.

Gas exchange is more of a problem, however, for large, multicellular organisms. Fish and other complex organisms that live in water are so large that their cells cannot be in constant contact with the water. (Koromond & Essenfield, pp. 213-214)

This passage can make sense only to students who understand the fairly complex relationships among concentration, surface area, and rates of diffusion; relationships that make sense only if students know that molecules are in constant motion, that carbon dioxide and oxygen dissolve in water, and that molecular motion will cause substances in water to distribute themselves equally throughout the solution. The work of Osborne and Cosgrove (1983) and Novick and Nussbaum (1981) indicate that less than half of the students at the high school level comprehend the above aspects of the kinetic molecular theory well enough to apply them to situations such as this. Without an adequate understanding of the aspects of the kinetic molecular theory, students have the task of interpreting the situation based on their own misconceptions of what is taking place. The resulting interpretations are usually not at all like those that the authors or the teachers intended (cf., Smith & Anderson, 1986).

Chemistry texts also present the first principles or basic assumptions of the kinetic molecular theory without considering how the students' preexisting misconceptions will affect their interpretations of the text. For example, Metcalfe, Williams, and Castka (1986) state, "The three basic assumptions of the kinetic theory are 1) Matter is composed of tiny particles, 2) the particles of matter are in constant motion, 3) the total kinetic energy of colliding particles remains constant" (p. 219). The authors then immediately use these assumptions to explain expansion, pressure, density, diffusion, an ideal gas, and the gas laws.

This treatment ignores the many ways in which concepts related to gases are particularly difficult for students. For instance, Mas, Perez, & Harris, (1987) tested 199 students, ages 17-18 years. They found that 54% of the students did not conserve weight in physical changes involving gases. Fifty one percent did not conserve mass and 58% believed that gases rise naturally in a gravitational field. This is consistent with other work which indicates that most students cannot apply the traditional definition of matter (matter is anything that has weight and occupies space) to gases because they believe that gases do not have weight (Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1990). Novick and Nussbaum (1981) found that among students in the university as well as in high school, 50% did not attribute the uniformity of particle distribution in gases to inherent particle motion and over 60% did not picture a gas as having empty spaces between molecules.

In light of the students preexisting misconceptions, it is not surprising that most high school chemistry students have difficulty with Charles', Boyle's, Dalton's, and Gay-Lussac's Laws as well as Avogadro's principle and the mole concept. By presenting the basic assumptions of the kinetic theory and then moving quickly to the gas laws, students are being asked to accept a series of concepts that conflict sharply with their own beliefs. As a result, most students are forced to accept what the book and teacher say without it making sense to them and, therefore, little meaningful learning takes place.

This is evidenced by the studies that indicate that even at the college level many of these same student misconceptions are retained (e.g., Anderson, Sheldon, & DuBay, in press; Gabel, Samuel, & Hunn, 1987; Hollon & Anderson, 1985; Novick & Nussbaum, 1981). It is clear that our present K-12 science curriculum has failed to change students' misconceptions concerning the kinetic molecular theory or to teach the aspects of this theory in any meaningful way.

One exception to the general tendency of American curriculum materials to neglect the kinetic molecular theory was the Houghton Mifflin Science series (Berger, Berkheimer, Neuberger, & Lewis, 1979), which included a nine-week unit on "Models of Matter" at the sixth-grade level. The principle author of the "Models of Matter" unit was Glenn D. Berkheimer, the first author of this paper. Because we continue to believe that this topic should play an essential role in the middle school curriculum, we set out to revise and improve the "Models of Matter" unit.

Description of the Project

This project was conceived as an exploration of the possibilities of improving the quality of commercial teaching materials through the use of research on cognitive structure and conceptual change. During the last 10 years, cognitive science researchers have produced research findings that have great potential for increasing students' understanding of science. However, commercial publishers continue to produce textbooks and teacher's guides in traditional ways, not taking advantage of these cognitive science research findings or methods.

This project developed a prototype unit which utilized an alternative approach to curriculum development. The unit was a rewritten version of the existing "Models of Matter" unit. Development and fieldtesting took place in the classrooms of all 15 sixth-grade science teachers in a middle-sized Midwestern industrial city surrounded by more affluent suburbs. The students in these classrooms were 60% Caucasian, 25% Black, and 15% other ethnic minorities, including Hispanics and recent immigrants from several Southeast Asian nations. Only one of the teachers with whom we worked had a degree in science. The others were mostly elementary teachers who had moved to the middle schools when the district had changed from a junior high based system.

The project lasted two years. During Year 1 the existing "Models of Matter" unit was used in the sixth-grade classes of four collaborating teachers to determine to what extent the students possessed the misconceptions that had been anticipated from previous research and whether the students possessed unanticipated misconceptions. For the purpose of assessing the effectiveness of the original unit, eleven other teachers also taught the "Models of Matter" unit and a posttest was given to their students. During Year 2 both the student materials and teacher's guide were rewritten based on the data collected from these classes. The rewritten unit, "Matter and Molecules," was pilot tested with the same four collaborating teachers with their new sixth-grade classes to determine to what extent student achievement increased. Based on pilot test data, the student materials and teacher's guide were revised for use by the other 11 sixth-grade science teachers and a posttest was given to their students.

Neither unit made use of specialized laboratory equipment or information-processing technology. Inservice training was limited to a single full-day workshop for all but the collaborating teachers. Even with this limited training it was clear that the new version of the unit had substantial effects on the teachers' content knowledge, planning, and teaching behavior, and on the way that they thought about their students' scientific cognition. Student achievement also improved substantially: Overall, students mastered about 50% of the scientific goal conceptions when they studied the new unit, compared with 25% for the old.

The products of the project include the teaching materials for the new, revised unit, entitled "Matter and Molecules." The unit is available in the form of a Science Book or student text, and an Activity Book that includes text-related questions and laboratory activities, and their accompanying

teacher's guides (Berkheimer, Anderson, & Blakeslee, 1988; Berkheimer, Anderson, Lee, & Blakeslee, 1988). In addition, project staff members have written three papers for presentation at national conventions and later publication. The first paper (Berkheimer, Anderson, & Blakeslee, 1990) describes the development process itself and the instructional strategies that were built into the unit. A second paper (Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1990) describes findings from research on student conceptions associated with the project and reports on student achievement using the unit. This paper focuses on the curricular problems involved in designing this unit.

Major Findings About Student Conceptions

The major goal of the unit was the same in both its original and its revised versions: to teach students to use the kinetic molecular theory (the idea that all substances are made of molecules that are constantly in motion) to explain the nature and structure of matter and physical changes of matter, including dissolving, expansion and compression of gases, thermal expansion, and changes of state. The new unit was different from the old, however, in that curriculum development was preceded by a thorough investigation of students' conceptions of the topic and of their learning from the previous unit. These investigations involved (a) clinical interviews administered to 24 students before and after instruction each year, (b) pretests administered to about 100 students in the classrooms of the four collaborating teachers each year, and (c) posttests administered to over 300 students in the classrooms of all 12 sixth-grade science teachers in the district each year. A detailed report on the results can be found in Lee et al. (1990).

These investigations of student conceptions and student learning led us to a substantial rethinking of what students would have to learn to achieve the

unit goals. The nature of these revisions is illustrated by the contrast between Table 1, which summarizes the conceptual content of the "Models of Matter" unit, and Table 2, which summarizes the conceptual content of the revised "Matter and Molecules" unit. These tables are different with regard to both their conceptual content and their implicit assumptions about the learning process.

The conceptual content of Table 1 corresponds roughly with the content of the Molecular Conceptions in Table 2; the Macroscopic Conceptions were added as a result of the research. We discovered that many of the most important problems that students encountered in trying to reach the goal of using the kinetic molecular theory to explain phenomena did not have to do with their understanding of molecules at all; instead their difficulties arose from incorrect or partially correct ideas about what substances were changing and how they were changing. Thus, achieving the goal of the unit required recognition of learning that would have to occur at the macroscopic as well as the molecular level. This issue is discussed in more detail below.

The form of Table 2 is also different from the form of Table 1, indicating that the two tables are based on different assumptions about the nature of student learning. Table 1 consists of a list of ideas to be learned, whereas Table 2 contrasts the ideas to be learned (scientific goal conceptions) with ideas that are common among students at the beginning of the unit (naive conceptions). Thus Table 2 depicts the learning of these ideas as a process of conceptual change, rather than simply as a process of adding new knowledge.

There were also important differences in the way that the activities or behaviors that students would learn to engage in for the two units were described for the two units. In the "Models of Matter" unit these activities were described as scientific processes: observing and describing,

Table 1

The 12 Principles of the Small Particle Model

Houghton Mifflin Science*

1. All matter is made up of particles.
2. Particles of matter are very small.
3. Particles of matter have spaces between them.
4. Particles of matter are in constant motion.
5. Particles of matter move faster when the matter is heated.
6. Particles of matter usually move farther apart when the matter is heated.
7. In the gas phase, the particles of matter are far apart and move freely.
8. In the solid phase, the particles of matter are packed together in a pattern and move within a small space.
9. In the liquid phase, the particles of matter are loosely clustered together and move about more than in solids.
10. Matter can be changed from solid to liquid and from liquid to solid.
11. Matter can be changed from liquid to gas and from gas to liquid.
12. Particles of matter attract each other.

*From: Berger, Berkheimer, Neuberger, & Lewis, 1979, p. T-324.

Table 2: Students' Misconceptions about Aspects of Kinetic Molecular Theory

CATEGORY	MACROSCOPIC		COMPARISON (%)				MOLECULAR		COMPARISON (%)			
	Contrast		Comparison (%)				Contrast		Comparison (%)			
			Yr 1		Yr 2				Yr 1		Yr 2	
			Pre	Post	Pre	Post			Pre	Post	Pre	Post
1. Nature of matter	Goal: Solids, liquids, and gases (including smells) are matter and take up space; Other things (e.g., heat, light) are not matter and do not take up space. Matter is conserved in all physical changes.	Naive: Classification is based on irrelevant properties (e.g., something you can see or feel). Gases and non-matter are incorrectly classified. Transformations conserve substances but not necessarily mass. Substances are transformed during physical changes (e.g., water to air, air to water). Substances disappear and cease to exist.	4.3	20.9	5.0	46.6	Goal: All matter is made of submicroscopic particles or invisible molecules. Molecules are constantly moving and have nothing but empty spaces between them.	Naive: No molecular notion initially. In learning about molecules, non-matter is described as molecular (e.g., heat molecules). Molecules are in substances. Molecules may be comparable in size to dust specks, cells, germs, etc. Molecules may sometimes be still (especially in solids) or move by external forces.	6.0	35.6	5.4	62.1
2. States of matter	Goal: Gases can be compressed, and spread evenly through the spaces they occupy.	Naive: Gases move from one place to another when compressed or expanded, and are unevenly distributed.	3.0	21.1	3.8	49.6	Goal: The three states of matter are differentiated based on the arrangement and motion of molecules in each state. Molecular motion continues independently of observable movement of substances.	Naive: States of matter are differentiated based on observable properties only (e.g., solids are heavy). Observable properties of the state are attributed to the molecules themselves (e.g., molecules are hard in solids), or molecules share in observable properties (e.g., molecules move in gases and liquids, but not in solids.)	2.5	27.3	1.9	52.7

CATEGORY	MACROSCOPIC						MOLECULAR					
	Contrast		Comparison (%) ^a				Contrast		Comparison (%) ^a			
3. Thermal expansion	<u>Goal:</u> Substances expand when heated.	<u>Naive:</u> Substances (especially solids) "shrivel up" when heated; expansion of gases is explained in terms of movement of air (e.g., hot air rises).	Yr 1		Yr 2		<u>Goal:</u> When a substance is heated, molecules move faster and farther apart.	<u>Naive:</u> Molecules themselves are changed by heating (e.g., molecules become hot, or molecules expand). No relationship between molecules moving faster and farther apart.	Yr 1		Yr 2	
			Pre	Post	Pre	Post			Pre	Post	Pre	Post
			10.9	67.7	17.9	79.7			3.0	36.2	1.4	58.0
4. Dissolving	<u>Goal:</u> The solute changes from a visible to an invisible form during dissolving.	<u>Naive:</u> The solute "disappears", "melts", or "evaporates".	Yr 1		Yr 2		<u>Goal:</u> Molecules of solute break away and mix with molecules of solvent.	<u>Naive:</u> No molecular notion initially. Focus on observable substances, or molecules themselves "dissolve."	Yr 1		Yr 2	
			Pre	Post	Pre	Post			Pre	Post	Pre	Post
			9.9	21.4	7.5	66.5			1.0	19.5	1.9	58.1
5. Changes of states of matter	<u>Goal:</u> Air contains invisible water vapor, and water vapor in air condenses on cold objects.	<u>Naive:</u> No recognition of water vapor in air, or liquid water changes into air, and vice versa. Condensation is a reaction between heat and coldness.	Yr 1		Yr 2		<u>Goal:</u> Heating and cooling make molecules of substances move faster or slower, causing changes of state in terms of their arrangements and motion.	<u>Naive:</u> Heating and cooling make molecules themselves change (e.g., molecules "boil", "evaporate"), or molecules share in observable properties of substances (e.g., molecules begin to move when heated.)	Yr 1		Yr 2	
			Pre	Post	Pre	Post			Pre	Post	Pre	Post
			2.0	5.8	0.5	30.8			3.0	27.8	1.2	41.4

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^a:Percentage of students who demonstrated adequate understanding of scientific goal conceptions

investigating and manipulating, organizing and quantifying, and generalizing and applying. In contrast, the activities students were to engage in for the "Matter and Molecules" unit were described primarily as applications of scientific knowledge: describing, explaining, making predictions about, and controlling the world around us. These contrasts are discussed in detail by Berkheimer, Anderson, & Blakeslee (1990).

Thus the research on student conceptions led us to a substantially different understanding of what students would have to learn in order to accomplish the main goal of the unit. This new understanding led, in turn, to substantial revisions in both the curriculum or content of the unit and methods of instruction. The instructional changes are discussed by Berkheimer, Anderson, & Blakeslee (1990), a paper which focuses on the curricular issues that we encountered while revising the unit.

Curricular Issues

Among the curricular issues that we encountered, the most important concerned (a) the development of both macroscopic and molecular conceptions, (b) the epistemological status of molecules, (c) the physical characteristics of molecules, (d) the nature of scientific explanations, and (e) the need to balance scientific elegance and student comprehension. Each of these issues is discussed below.

Macroscopic and Molecular Conceptions

As described above, the main focus of the commercial unit was on using kinetic molecular theory (called "the small particle model") to explain physical changes in substances. Interviews with students revealed that there were often difficulties with their explanations that had nothing to do with their understanding of molecules per se. Students who believed that substances

"shrivel up" when heated, for example, had trouble explaining thermal expansion. The idea that all matter is made of molecules was problematic for students who did not believe that gases such as air and helium are matter--or for those who believed that forms of energy such as heat and light are matter.

More general problems were also apparent at the macroscopic level. For example, nonconserving explanations of physical changes were common: Many students believed that substances ceased to exist when they dissolved or evaporated, or that condensing water formed on the spot. Others believed that substances changed mass when they changed state. It was also often difficult for students to decide just what changes in what substances needed to be explained. They explained how sugar escapes from a tea bag immersed in water, for instance, by focusing on what happens to the tea bag when it gets wet rather than on what happens to the sugar when it gets wet.

In general, we discovered that these sorts of difficulties at the macroscopic level were often important barriers to the development of successful molecular explanations. Thus teaching students to use the kinetic molecular theory generally involved also teaching them how to analyze a situation at the macroscopic level.

These considerations led to two kinds of modifications in the unit content. First, we carefully considered our choices of examples and problems for the students and used only those that did not involve excessive ancillary teaching about macroscopic concepts. Second, we added a number of macroscopic conceptions to the unit content, as indicated by the organization of Table 2. In the revised unit there is almost as much time devoted to teaching about macroscopic properties of substances and how they change as there is time devoted to teaching about molecules and their properties. As a result of this change of emphasis, students using the new unit were much more successful in

making connections between ideas about molecules and observable events in the real world.

The Epistemological Status of Molecules

The commercial unit opened with a series of lessons in which students considered the effectiveness of various models--the "push model," the "shake model," the "sticky model," and the "small particle model"--in explaining phenomena involving mixing and dissolving. The purpose behind this approach was to help students understand two important points about how scientific theories are developed and tested. First, scientific knowledge is inherently uncertain; rather than discovering the "truth" about the world, scientists invent alternative models or hypotheses. Second, the best model is selected on an empirical basis; it is the one that is most successful in making predictions about phenomena. Although this seemed like a good idea, our observations of classroom teaching and our discussions with the collaborating teachers led us to question the appropriateness of the approach for both pragmatic and theoretical reasons.

At a pragmatic level, our observations revealed that the alternative models seemed to create conceptual confusion without producing epistemological insight for most students. There was little evidence that they were ready to understand the first of the two intended points: the inherent uncertainty of scientific knowledge. They saw statements about the world as being true or false, fact or fiction. They could see that they might not know whether a given idea was true or false, but they were not ready to accept the existence of a class of statements about the world whose truth or falsehood might not be decidable.

An even more troubling set of issues concerning the second intended point of the alternative models was revealed by the students' ways of deciding which

model was best. The second intended point of the alternative model was that the best model is chosen on the basis of empirical evidence. Many students found the push model, which suggested that substances mix because the solute "pushes" its way into the solvent, more satisfying and easier to use than the more complicated small particle model, and they preferred to continue making adjustments to the push model rather than reject it for the small particle model. The remainder of the unit, however, was devoted to the development of the small particle model, so teachers who wished to continue with the unit as written were faced with the uncomfortable problem of convincing their students (or simply telling them) that they had drawn the wrong conclusions from the evidence.

These practical difficulties led us to a number of questions about the validity of the epistemological points themselves. With regard to the first point (the uncertainty of scientific knowledge), for example, just how uncertain are we about the existence and nature of molecules? Are they merely useful theoretical constructs or are they actual little objects that we can describe in some detail? The answers to these questions are not as clear as suggested by the original unit's treatment of the alternative models.

While it is true that explanations in the physical sciences depend heavily on invented theoretical constructs such as force, energy, or velocity, explanations in the biological sciences often work quite differently. Biologists often explain the workings of a system in terms of the workings of subsystems that they believe to be quite real, not mere theoretical constructs. We explain the movement of a person's arm, for instance, in terms of the actions of her muscles, which we believe to be real even though we cannot see them. In turn, we explain the actions of the muscles in terms of actions of muscle cells, the actions of muscle cells in terms of the actions of their

organelles, and the actions of the organelles in terms of the molecules of which they are composed. At what point in this chain of explanations have we crossed the line between real subsystems and theoretical constructs?

We also came to consider the second epistemological point (that models are chosen on the basis of evidence) as problematic. The evidence considered in the first part of the unit had to do with mixing and dissolving. Generations of scientists before Dalton had observed those phenomena without being convinced of the validity of the small particle model, so why should that evidence be convincing to students? In fact, as historians of science such as Kuhn (1970) and Toulmin (1963, 1972) have pointed out, the process of selecting among competing models is far more complex than the treatment of the alternative models suggests. Theories are judged not on the basis of particular "key experiments," but on the basis of extensive bodies of evidence that accumulate over long periods of time and on the basis of the role that they play in the "intellectual ecology" of the scientific community. Thus we concluded that, in trying to represent certain aspects of the scientific enterprise, the alternative models presented a picture that was distorted in other respects.

Ultimately, these considerations led us to drop the alternative models in the revised version of the unit. The revised unit presents molecules not as theoretical constructs but as real entities, the "pieces" of which matter is made. We did not emphasize either the uncertainty of our knowledge about molecules or the nature of the evidence on which our belief in their existence is based. The treatment in the new unit did retain another important epistemological message: that the kinetic molecular theory consists of not simply facts or propositions about the nature of substances, but intellectual tools that can be used to describe and explain the properties of substances and

how they change. In as much as students appreciate the tool-like character of scientific theories, the issue of their truth becomes less salient. Our criteria for judging tools focus on usefulness more than truth: We keep a tool as long as it is useful and discard it when a more useful tool becomes available.

This resolution of the problem has not proved to be entirely successful. Upon discovering how small we believe molecules to be, some students raise questions about how we can know that they exist at all. The unit in its present form does not answer those questions particularly well, so some students remain dissatisfied. Perhaps, though, this is not an altogether undesirable state of affairs. The students are raising important epistemological questions themselves rather than being confused by the unit's treatment of issues that they are not intellectually ready to consider.

Physical Characteristics of Molecules

In an effort to avoid unnecessary complexity, the commercial unit avoided the word "molecules" entirely. It referred instead to "small particles," and did not distinguish one kind of small particle from another. In the end, it appeared that this attempt at simplicity caused more problems than it resolved. Some students believed that there was a single generic type of "small particles," which floated in various substances like specks of dust in the air (in fact some students believed that specks of dust were the small particles that the text referred to). Other students thought that there was a single generic type of small particles of which all substances were made.

The revised unit therefore includes more details about the nature and structure of molecules than its predecessor. Molecules are referred to by name, and the structures of a half dozen sample molecules are introduced (water, alcohol, sugar, oxygen, nitrogen, carbon dioxide), not so they can be

memorized but so that students can appreciate how and why molecules are different from one another. The small size of molecules is also emphasized; molecules are pictured next to other small objects with which students are familiar (cells and specks of dust) so that students can appreciate that molecules are much smaller.

This additional information about the physical properties of molecules helped many students to resolve issues that had been confusing to students using the old unit. They understood clearly that they could not see individual molecules, and that motion need not be visible in a substance for its molecules to be in motion. They were also more likely to propose explanations for physical changes involving the motion and arrangement of molecules, rather than their transmutation or destruction.

The Nature of Scientific Explanations

Previous research by several investigators (e.g., Hesse & Anderson, 1988; Solomon, 1983) has revealed that students often have trouble understanding what constitutes an acceptable scientific explanation. When asked to explain something, they are likely to rely on analogies or descriptions or simple repeated phrases and definitions. In contrast, scientists consider an explanation to involve a detailed account of the relationship between relevant scientific theories and the system or phenomenon to be explained.

Some students discovered, for example, that the phrase, "The particles move faster and farther apart," could be invoked in a variety of situations, such as those involving thermal expansion, melting, and boiling. What they did not appreciate was that simply invoking this phrase did not constitute an adequate explanation unless they specified which molecules they were talking about, why they were moving faster and farther apart, what else might be happening to them, and how the molecular process was connected with the

observable phenomenon. In the end, these students did not come to appreciate the power or the importance of scientific explanations, seeing them instead as involving the trivial repetition of phrases or the use of their own common sense.

In the new unit this difficulty was addressed by developing a heuristic to guide students in their attempts to produce coherent scientific explanations. The heuristic reminded students that good scientific explanations should (a) identify the substance that is changing and specify how it is changing, and (b) explain the change in terms of molecules and their motions. This heuristic helped students to decide for themselves when they had developed an adequate explanation and encouraged them to develop more complex and complete explanations. It also provided a basis for communication between teachers and students about the quality of various suggested explanations. Thus their understanding of scientific content was enhanced by the inclusion of more general information about the nature of scientific explanations.

Balancing Scientific Elegance and Student Comprehension

Scientific explanations tend to be elegant and parsimonious. Often the most elegant are the most scientifically advanced, the most abstract, and the most difficult for students to understand. Thus the design of teaching materials involves dealing with a constant tension between elegance and comprehensibility. Theories and explanations that appear simple and elegant can sometimes be very difficult for students to understand because the simplicity is embedded deep within the complex conceptual ecology of a scientific theory. In these situations it is sometimes necessary to settle for explanations that are less elegant and satisfying to the professional but are more accessible to students.

For example, the idea that molecules attract each other played an

important role in the original unit, and it was used to explain a variety of phenomena, including condensation, freezing, and surface tension. Unfortunately, understanding and using this idea turned out to be very difficult for most students. It answered a set of questions that they did not spontaneously ask and it was useful only to students who already understood many other complex ideas. It did not occur to most students, for example, to wonder why molecules would cling together when they started to move more slowly; the students were willing to accept that they did. Ultimately, the surface tension activities were dropped from the unit. While the idea of attraction was used in the text explanations of condensation and freezing, it was not emphasized.

Summary

We have described a series of curricular decisions that were made during the development of the "Matter and Molecules" unit. While the general goal of the unit remained the same as the general goal of its predecessor (to help students use the kinetic molecular theory to explain the nature of matter and physical changes in matter), there were many changes at a more detailed level. Some content was added, such as the macroscopic conceptions, the heuristic guiding the development of explanations, and information about physical characteristics of molecules. Other content was dropped, such as the alternate models and the activities involving surface tension. There were many other changes in approach or emphasis. Information about students' conceptions and their learning was not the sole determining factor in any of these decisions, but it played an important role in all of them. Because this information was available to us, the curricular decision-making process was better informed and more constrained than it otherwise would have been.

Conclusion

In as much as there is a generally accepted science curriculum in the United States, it is a product of market research by publishers, tinkering and guesswork by curriculum developers, and decisions made by various organizations about what to include on achievement tests. As a result, most students experience science in schools as a mishmash of relatively unconnected topics and understand little of the content that is "covered."

A fundamental rethinking of the science curriculum is clearly in order, and it seems that research on cognitive structure and conceptual change could play an important role in such a process. Yet so far this has not occurred, for a number of reasons. Conceptual change researchers have generally focused on individual topics that are accepted parts of the curriculum (e.g., heat, or photosynthesis, or genetics). Their investigations have almost always led to the conclusion that curriculum and instruction in those topics need to be drastically revised, but relatively little has been written that focuses on the relationship between conceptual change research and the curricular decision-making process, either within topics or on a larger scale. This paper is our attempt to make explicit some of our thinking about those relationships.

Curricular decision making is a difficult, time-consuming process involving many factors that cannot be addressed by research. In particular, research can do relatively little to help us decide what scientific knowledge is most valuable. No individual could ever master all scientific knowledge, so how can we decide which knowledge is most important for the students in our schools? There are no perfect answers to this question. What our students will most need to know when they are adults will depend on social and economic developments that we cannot fully foresee, on the particular roles that they will play in our society, and on values and beliefs that not all people share.

To make wise judgments about content therefore requires judgments about social, political, and economic issues that cannot be fully analyzed by research.

Nevertheless, we hope that the issues discussed in this paper illustrate how conceptual change research can inform curricular decisions. The research helped us to become aware of a number of curricular issues and to resolve them in productive ways and it helped us to address problems of curriculum using strategies that were informed by knowledge of students' cognition and development. These informed strategies made curriculum development more like engineering and less like the trial-and-error tinkering that has prevailed in the past.

We hope that the approach to the curriculum development described in this paper will stimulate fruitful discussions among researchers, science educators, and curriculum specialists. It is hoped that such discussions will lead to the evolution of a science curriculum that is more coherent and more understandable by students than the current curriculum.

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